National Aeronautics and Space Administration

Application of Fault Management Theory to the Quantitative Selection of a Launch Vehicle Abort Trigger Suite

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Space Launch System

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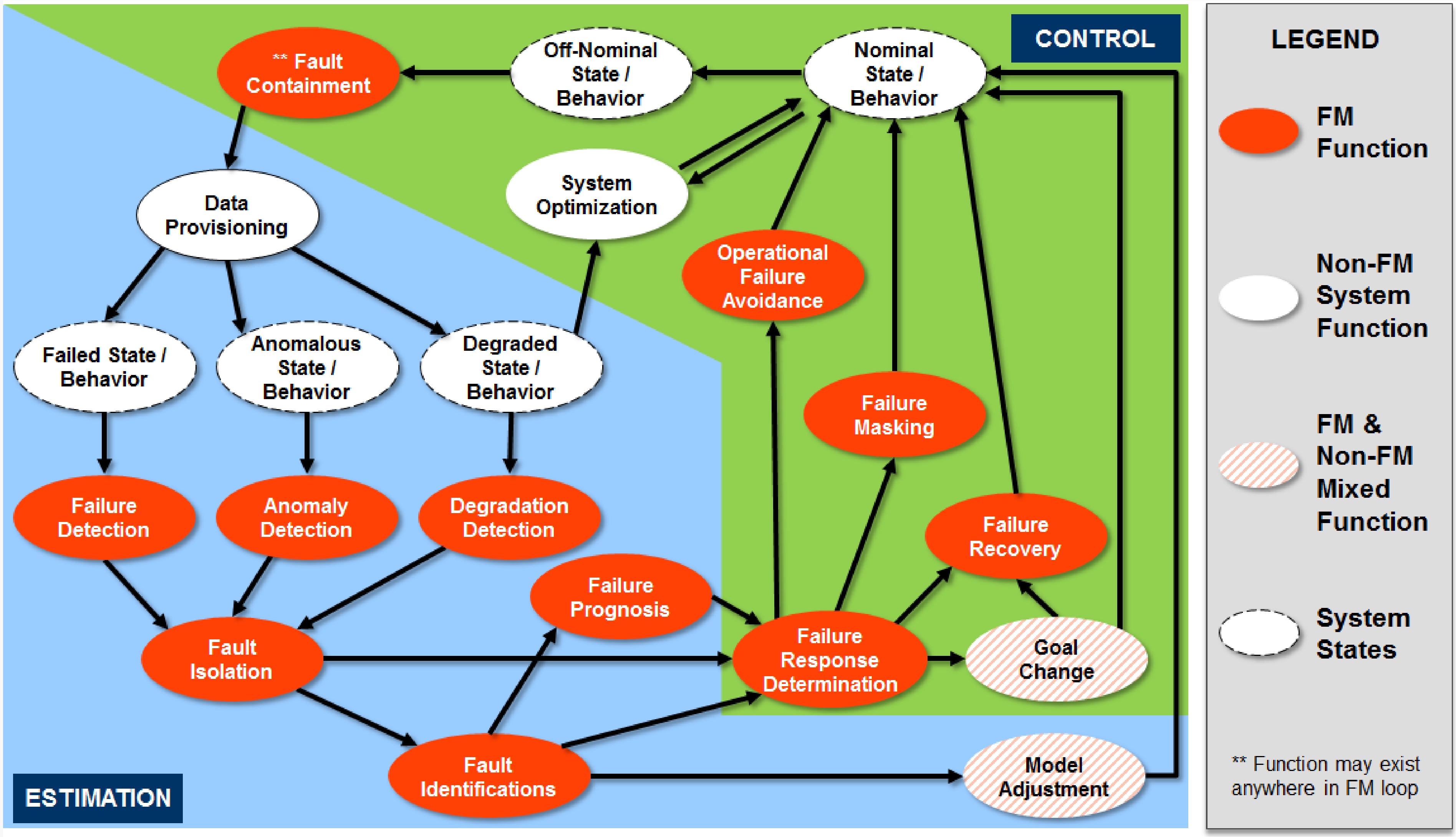
Outline

- Simplified Fault Management (FM)
- Application of System Health Management (SHM) theory for NASA Space Launch System (SLS) Abort System
- What are Launch Vehicle Abort Triggers
- Application and Example
- Limitations and Conclusions

What is System Health Management

- **SHM addresses activities that are described under several names:**
  - Prognostics and Health Management
  - Fault Protection
  - Vehicle Health Monitoring and/or Management
  - Fault Detection, Isolation and Response (FDIR)
  - Diagnostics, Maintainability, Reliability, and Availability
- **Historically ad hoc set of processes and technologies that aim to predict, detect, diagnose, and response to failures**
- **Basis for unified theory of SHM goes back nearly 20 years, and this theory provides the conceptual framework for the field and operational subset, Fault Management**
  - FM theory can be considered as an extension of control theory [FM Control Loop (FMCL) Theory]
- **Purpose of SHM is to "Preserve the system's ability to function as intended"**

Fault Management Functions as State Estimation and Control

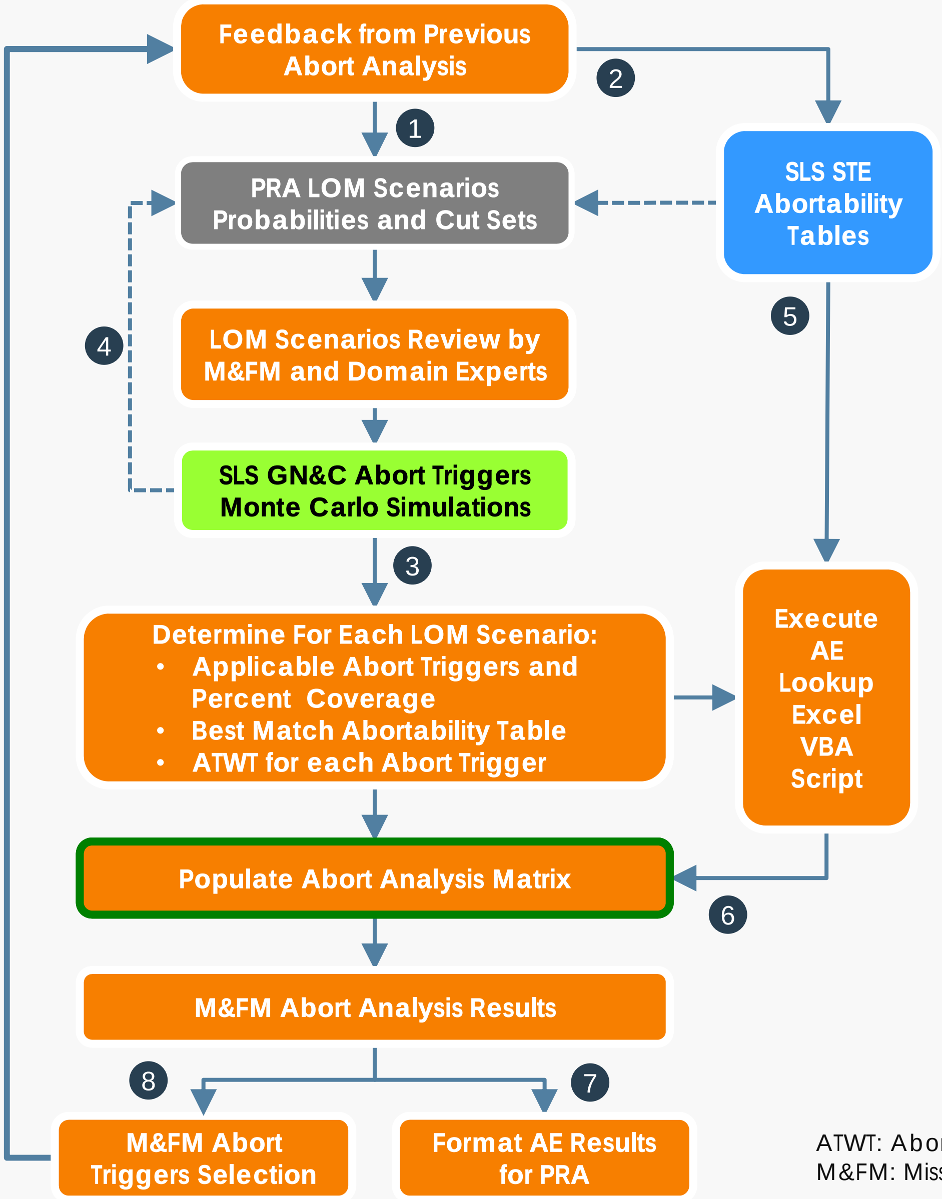


Applying SHM Theory to SLS Abort Detection and Response Logic

- **Most crew threatening failures result in:**
  - Launch vehicle explosions or loss of control
  - Inability to achieve orbit but able to maintain attitude control
- **Abort Triggers exist to enable crew escape from the hazard**
  - An abort response cannot occur unless the abort condition is detected
  - If an abort condition is detected, the SLS can send an Abort Recommendation message to the MPCV, or a Warning message if the failure develops slowly
- **Abort Triggers can be on SLS, MPCV, Launch or Mission Control Center, or Flight Crew**
- **Improvement to crew safety is measured as Loss of Crew (LOC) Benefit gained by adding Abort Triggers to the design**
  - LOC Benefit is the highest-level metric
  - Calculated through Loss of Mission (LOM) Scenarios probabilities and associated Abort Effectiveness (AE) values
- **Provides crucial information to…**
  - Assess probabilistic LOM and LOC requirements
  - Risk-informed design to select abort triggers
  - Develop operational procedures

Block I SLS 70 mT

SLS Abort Trigger Analysis Approach



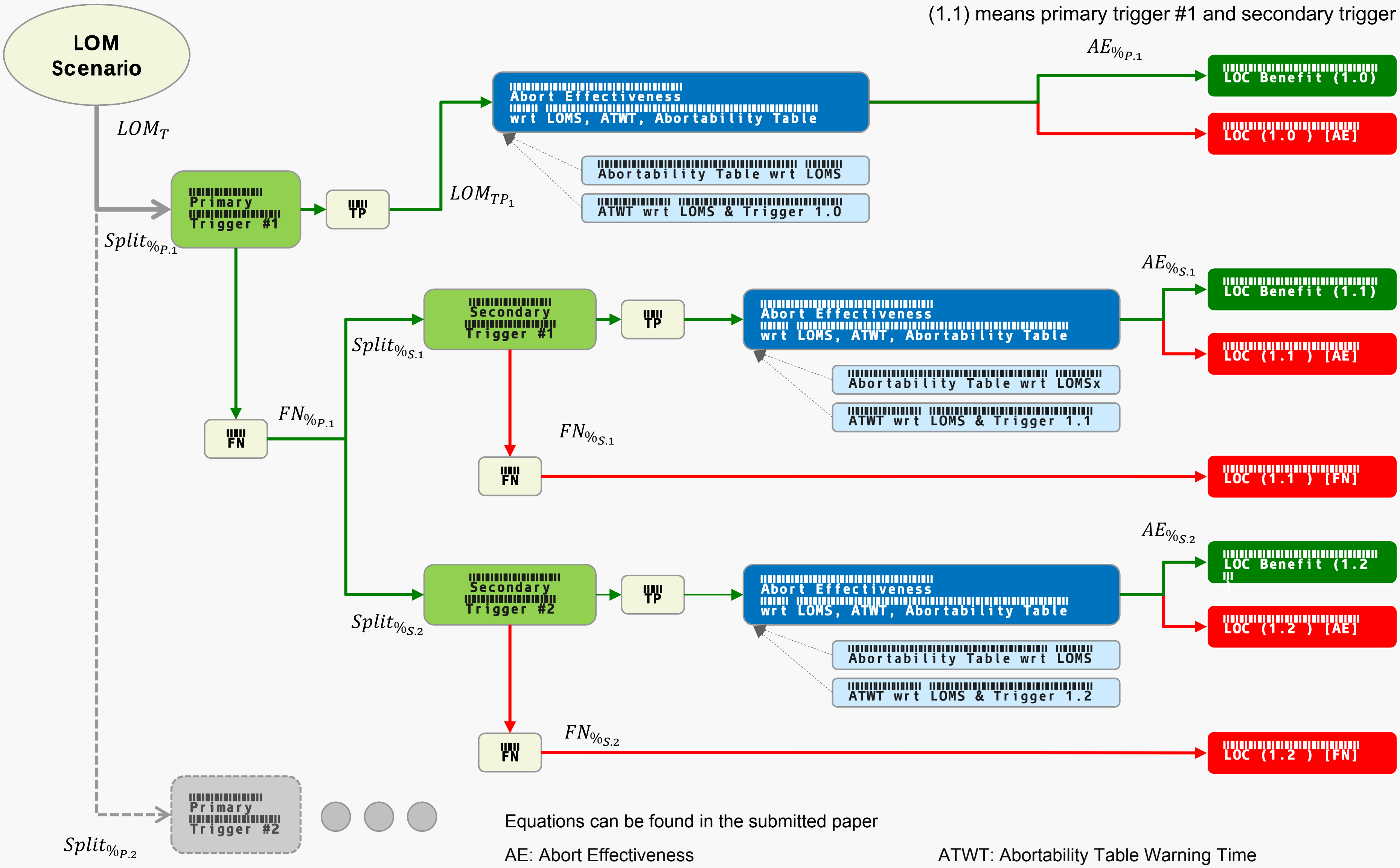
1. New, deletion or changes to existing LOM Scenarios.
2. New or changes to existing Abortability Tables such as: ATWT range, flight termination system delay time, and changes in failure scenarios.
3. GN&C AE estimates for vehicle Loss of Control Scenarios.
4. Percent vehicle thrust vector control failures that can be successfully controlled and lead to mission success. SLS GN&C provides inputs to PRA prior to LOM Scenarios delivery to M&FM.
5. Structures and Environments (STE) Abortability Tables are associated with SLS vehicle explosion cases, such as CSE explosion.
6. AE lookup as a function of ATWT, Abort Trigger, Abortability Table and mission phase.
7. AE values for each LOM Scenario-mission phase combination for inputs into PRA software to calculate official LOC and inputs into Cross-Program PRA model.
8. AE and LOC Benefit values are used by M&FM to assess Abort Trigger Effectiveness, recommendations for new or removal of Abort Trigger, and Abort Trigger designs.

ATWT: Abortability Table Warning Time
M&FM: Mission & Fault Management

AE: Abort Effectiveness
VBA: Visual Basic for Application

Example of Abort Analysis Matrix's Logic Flow Diagram

(1.1) means primary trigger #1 and secondary trigger #1



Equations can be found in the submitted paper

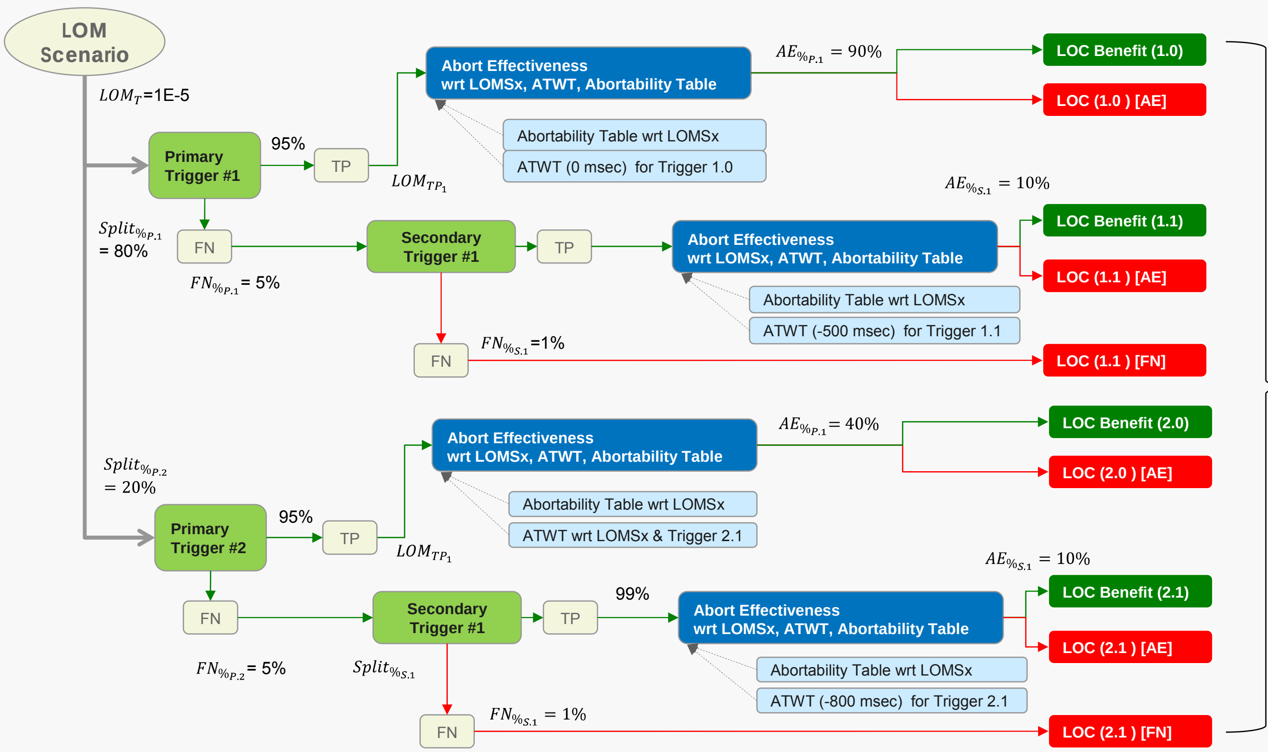
AE: Abort Effectiveness
FN: False Negative
TP: True Positive

ATWT: Abortability Table Warning Time
LOMS: Loss of Mission Scenario
wrt: With respect to

Example Calculation

- **Prob. LOM = 1E-05 per mission**
- **Two primary triggers, P1 and P2, and one secondary trigger, S1**
- **Point estimates shown**
- **AE is estimated with respect to LOM scenario, trigger, ATWT and abortability table type**

TRIGGERS			
Parameter	P1	P2	S1
Trigger Coverage %	80%	20%	100%
False Negative	5%	5%	1%
ATWT (ms)	0	-500	-800
AE (%)	90%	40%	10%



ATWT: Abortability Table Warning Time
AE: Abort Effectiveness
FN: False Negative
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wrt: With respect to

LOM Scenario Abort Effectiveness ~ 76.5% for the example abort trigger suite

LOC Benefit ~ 7.7E-06
LOM = 1E-05
LOC = 2.4E-06

Value of LOC Benefit Calculation

- **Represents the value of FM to mitigate potential, impending, and actual failures that threaten human safety**
  - Value of these FMCLs depend on the probability of the failures that they mitigate
- **Useful in a comparative sense to assess different potential FM detections & responses**
- **Example, assume that the probability of achieving orbit is 90% (or Prob. LOM = 10%)**
  - If no abort action occurs, then LOM = LOC
  - If LOC requirement is set at 1% per mission, then Abort Triggers and abort responses must reduce the LOC accordingly
  - The difference between these values is the required amount of LOC Benefit that must be provided
  - Abort Triggers are worthwhile only if they provide “significant” value in driving LOC down to the required level
- **It is necessary to also estimate costs, such as the actual monetary and schedule costs to allow Program Managers to make informed decision**

Key Limitations

- **Capturing and propagation of uncertainties**
  - Each group performed their own calculations with their own uncertainties and assumptions; difficult to integrate them all
  - In M&FM, used Worst-on-Worst, Best-on-Best bounding instead of Monte Carlo Simulations
- **Several SLS groups already performed analyses that generated data similar to what was ultimately needed to perform the Abort Trigger Analysis**
  - S&MA PRA
    - M&FM required more detail for some failure scenarios than PRA would otherwise have generated
  - GN&C analyses of GN&C Abort Triggers already existed
    - M&FM provided better framework to incorporate and interpret the data
  - STE already performed blast overpressure, debris and fireball analyses
    - M&FM provided inputs to STE to define needed analyses, and to define the structure for inputs to (warning times, phases, time steps and bounds), and outputs from (“abortability” / survivability) STE

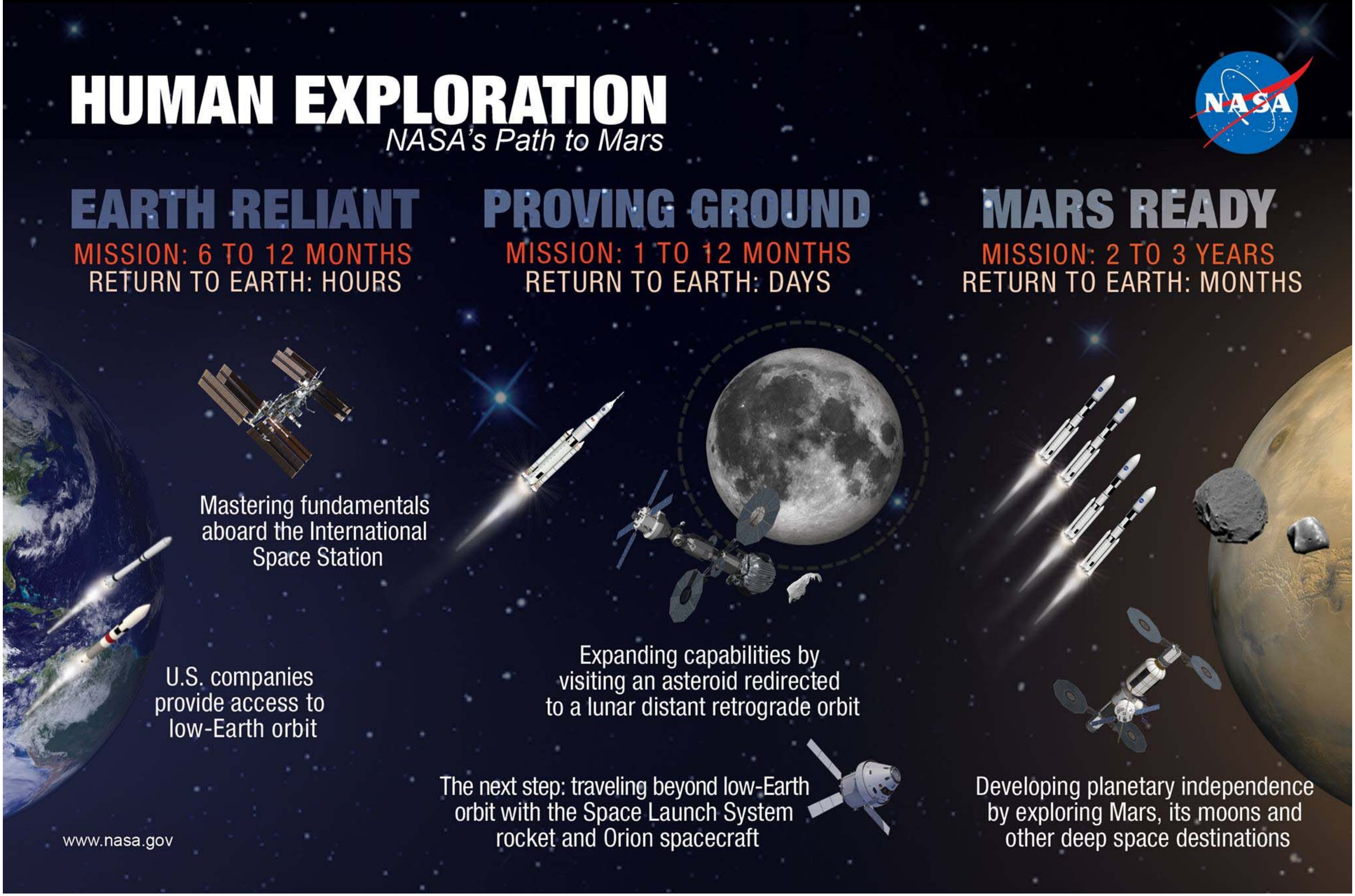
Conclusions

- **SHM/FM theory has been successfully applied to the selection of the baseline set Abort Triggers for the NASA SLS**
  - Quantitative assessment played a useful role in the decision process
- **M&FM, which is new within NASA MSFC, required the most "new" work, as this quantitative analysis had never been done before**
  - Required development of the methodology and tool to mechanize the process
  - Established new relationships to the other groups
- **The process is now an accepted part of the SLS design process, and will likely be applied to similar programs in the future at NASA MSFC**
- **Future improvements**
  - Improve technical accuracy
    - Differentiate crew survivability due to an abort, vs. survivability even no immediate abort occurs (small explosion with little debris)
    - Account for contingent dependence of secondary triggers on primary triggers
    - Allocate "Δ LOC Benefit" of each trigger when added to the previously selected triggers.
  - Reduce future costs through the development of a specialized tool
- **Methodology can be applied to any manned/unmanned vehicle, in space or terrestrial**

Thank You and Finally…

SLS is the first step in the **journey to Mars**

The Path To Mars



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